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To cite this article: R S Zavornitsyn *et al* 2019 *J. Phys.: Conf. Ser.* **1389** 012157

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Spin valve based sensor elements for full Wheatstone bridge

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Abstract. Present work deals with methods for creating opposite pinning directions in micro-objects based on a spin valve by one thermomagnetic treatment. The methods are based on the thermomagnetic treatment in spin-flop state of synthetic antiferromagnet. We use splitting the magnetic structure in spin-flop state of synthetic antiferromagnet to form opposite pinning directions in different micro-objects by one thermomagnetic treatment. The positive characteristic (dR/dH) was obtained in the two sensor elements of the full Wheatstone bridge, and the negative characteristic (dR/dH) in the other two elements.

1. Introduction

Based on GMR effect sensor elements are widely used to measure magnetic field. They have high sensitivity, small size and low cost compared to analogues (AMR, Hall sensors). Nanostructures of the spin valve can be used as a magnetic material for a GMR sensors. A spin valve includes two ferromagnetic layers separated by copper spacer, one of the layer is coupled by exchange interaction with adjacent antiferromagnetic layer. The second ferromagnetic layer is called as free.

One of the factors affecting the magnetic and magnetoresistive properties of a spin valve is anisotropy. Induced uniaxial anisotropy characterized by easy axis (EA) is formed in a spin valve during deposition in a magnetic field. The pinning direction (PD) arises as a result of the exchange interaction in ferromagnetic/antiferromagnetic interface. Shape anisotropy is present in planar magnetic micro-objects in addition to the types of anisotropy listed.

It is known that the mutual arrangement of EA and PD is one of the factors that determine the width of the free layer hysteresis loop. It is possible to reduce significantly the hysteresis by forming a crossed EA \perp PD configuration [1]. This can be achieved using thermomagnetic treatment (TMT). During heating the spin valve to the blocking temperature (T_b) the exchange interaction at the ferromagnet/antiferromagnet interface destroys. New PD forms by cooling in a magnetic field.

To increase the temperature range in which the sensor retains its functional characteristics, a spin valve with a synthetic antiferromagnet (SAF) is used. The SAF is a three-layer structure in which two ferromagnetic layers are coupled by antiferromagnetic exchange interaction through the ruthenium layer. The ferromagnetic layer closest to the antiferromagnetic is called pinned layer and the second ferromagnetic layer is reference. A feature of a spin valve with a SAF is a spin-flop state. At certain value of applied magnetic field (H_{sf}) the magnetic moments of the pinned and reference layers unfold at an angle of 180° and set perpendicular to the applied field. This property can be used to form a crossed configuration of the spin valve PD and the easy axis. It is known [2] that two magnetic phases with the



opposite PD can form in a spin valve in spin-flop state. The reason is that the magnetic moments of ferromagnetic layers in SAF, deviating from the H_{sf} direction can turn both clockwise and counterclockwise if these two directions are energetically equivalent [3].

To create magnetoresistive sensors, it is preferable to have a full Wheatstone bridge in which all sensor elements contribute to the output signal. This scheme allows to avoid temperature drift, to get a good linearity and signal level. It should be noted that to implement such a scheme, the two sensor elements must have a positive characteristic ($dR/dH > 0$), and the other two must have negative one ($dR/dH < 0$). This can be achieved if the opposite PD in the sensor elements are formed in pairs [4]. In [5], a method for manufacturing sensor elements with different PD using two-step sputtering and photolithography was demonstrated. It is also possible to change the PD by thermomagnetic treatment with the transmission of electric current through the some sensor elements [4]. In [6] it was reported a TMT method of creation different PDs in Wheatstone bridge elements based on spin valve with SAF. However, opposite PDs in the elements was not obtained.

The aim of our work is to form the opposite PDs in sensor elements using a single thermomagnetic treatment and features of the SAF in spin-flop state, thereby obtaining sensor elements with different differential characteristics.

2. Experiment

Spin valves with SAF [CoFeNi/Ru/CoFeNi] having the structure Ta(50Å)/(Ni₈₀Fe₂₀)₆₀Cr₄₀(t_{NiFeCr})/Co₇₀Fe₂₀Ni₁₀(35Å)/Cu(t_{Cu})/Co₇₀Fe₂₀Ni₁₀(35Å)/Ru(8Å)/Co₇₀Fe₂₀Ni₁₀(30Å)/Fe₅₀Mn₅₀(100Å)/Ta(50Å) with t_{Cu} =20 and 21 Å and t_{NiFeCr} =50 and 60 Å were fabricated by magnetron sputtering on glass substrates. The spin valves were used as magnetically sensitive materials for micro-objects.

We studied two types of micro-objects. The first one was micro-strips with width of 20, 60, 80 μm. The EA is deviated to the right or left at an angle of 15° from micro-stripe axis. The second one was micro-strips of 2 and 4 μm width having configuration of a Wheatstone bridge. The Wheatstone bridge was formed as diamond. The EA was directed along the long diagonal of the diamond. The angle between the EA and the direction of the strip element is equal to 15°.

Wheatstone bridge configuration was obtained by means of electron-beam lithography using an Inspect F scanning electron microscope (FEI). Micro-objects in the form of strips and contact pads were formed using optical lithography on an MJB4 installation (SUSS MicroTec).

Magnetoresistive measurements and thermomagnetic treatment in a helium atmosphere were carried out in an installation assembled on the basis of an electromagnet of Bruker and a temperature controller LakeShore 336. The resistance on field dependencies of each sensor element was measured by a pseudo four point probe method.

The field dependences of the resistance were measured for each micro-stripe. The magnetoresistance was defined as $\Delta R/R_s = [(R(H) - R_s)/R_s] \times 100\%$, where $R(H)$ is the sample resistance in a magnetic field and R_s is the resistance in the saturation field.

SOLVER NEXT multifunctional scanning probe electron microscope operating in atomic force microscopy (AFM) mode was used to study the fine magnetic structure.

3. Results and discussion

3.1. Splitting the magnetic structure at TMT in the spin-flop state

As it was mentioned TMT in spin-flop state leads to appearance of two magnetic phases with opposite PD if exchange-coupled moments of the pinned (\mathbf{M}_p) and reference (\mathbf{M}_r) layers turn both clockwise and counterclockwise.

In our experiments TMT in the $H_{sf} \parallel EA \parallel PD$ configuration leads to the formation of two new pinning directions PD1 and PD2 in the micro-stripe with a width of 100 μm. It is important to note that EA was parallel to micro-stripe axis.

The field dependences of magnetoresistance of the micro-stripe before and after TMT are shown in figures 1 and 2. Before TMT the shape of magnetoresistive curve is appropriate for a spin valve

(figure 1). It is clearly seen that there is one plateau with maximal magnetoresistance. The measurements were performed in the $H \parallel EA \parallel PD$.

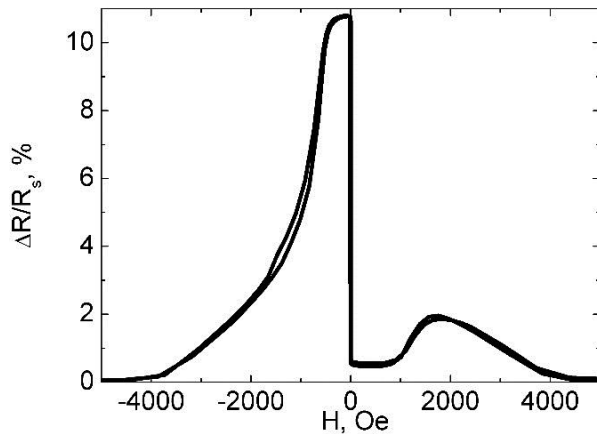


Figure 1. The field dependence of the magnetoresistance of the micro-stripe fabricated from Ta(50Å)/(Ni₈₀Fe₂₀)₆₀Cr₄₀(50Å)/Co₇₀Fe₂₀Ni₁₀(35Å)/Cu(20Å)/Co₇₀Fe₂₀Ni₁₀(35Å)/Ru(8Å)/Co₇₀Fe₂₀Ni₁₀(30Å)/Fe₅₀Mn₅₀(100Å)/Ta(50Å) before TMT.

After TMT the field dependence of the magnetoresistance has two plateaus, corresponding to the maximum value of the GMR effect (figure 2). Thus, two pinning directions PD1 and PD2 were formed at TMT with H_{sf} . Field in measurements was perpendicular to EA. New PDs $\perp EA$ and are directed parallel and antiparallel to the field applied in the measurement. Probably, in some areas the rotation of the magnetic moments of the pinned and reference layers occurred clockwise, and others counterclockwise with the formation of two magnetic phases.

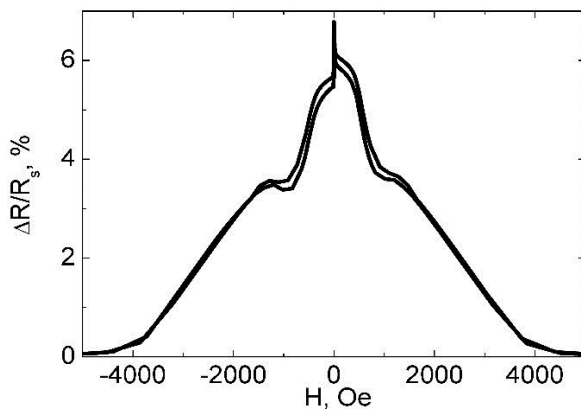


Figure 2. The field dependence of the magnetoresistance of a micro-stripe fabricated from Ta(50Å)/(Ni₈₀Fe₂₀)₆₀Cr₄₀(50Å)/Co₇₀Fe₂₀Ni₁₀(35Å)/Cu(20Å)/Co₇₀Fe₂₀Ni₁₀(35Å)/Ru(8Å)/Co₇₀Fe₂₀Ni₁₀(30Å)/Fe₅₀Mn₅₀(100Å)/Ta(50Å) after TMT.

Figure 3 shows the results of visualisation of the magnetic structure of the micro-stripe after TMT in the $H_{sf} \parallel EA \parallel PD$ applied parallel to micro-stripe axis. One can see the areas with different magnetic contrast in the image. We suppose that the reason of magnetic contrast appearance is the existence of two magnetic phases with opposite PDs in spin valve stripe.

Splitting the magnetic structure into two phases can be avoided by deflecting the H_{sf} field from any of the directions of anisotropy in the spin valve (stripe axis, PD or EA). In this case, the rotation of the magnetic moments of the reference and pinned layers during the spin-flop transition occurs equally over the entire sample area.

The deviation of H_{sf} from one of anisotropy axis sets the direction in which exchange-biased \mathbf{M}_p and \mathbf{M}_r will turn. We use this trend to form opposite pinning directions in different micro-objects by one TMT.

3.2. Uniaxial anisotropy as a factor affecting on pinning directions splitting

We studied micro-strips with a width of 20, 60, 80 μm in which EA was deviated to the left or to the right from micro-stripe axis (as shown in the inset in figure 4). TMT of the stripes was carried out in two configurations.

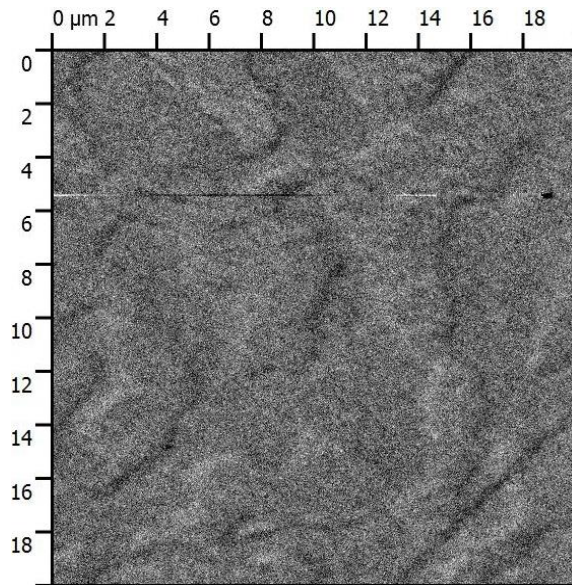


Figure 3. AFM image of the magnetic structure of micro-stripe divided into two magnetic phases after TMT in spin-flop state.

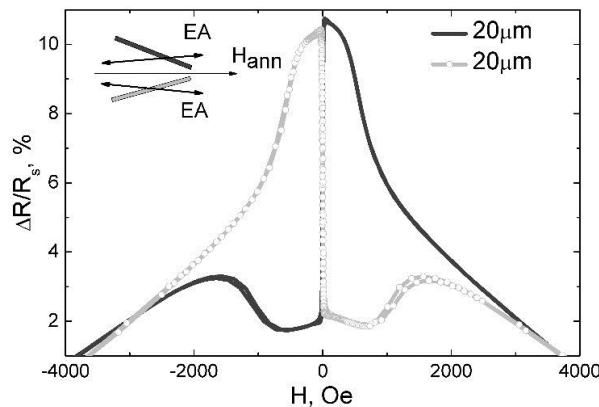


Figure 4. Field dependences measured for micro-strips with width 20 μm after TMT. Inset shows schematic arrangement of micro-strips, EA and the annealing field (H_{ann}) at TMT.

TMT included two stages. The first stage included annealing in a field of -9 kOe during 10 minutes at a temperature of 180°C. This temperature exceeds the blocking temperature for the antiferromagnet $\text{Fe}_{50}\text{Mn}_{50}$. The second stage was a similar annealing with further cooling in the spin-flop field $H_{\text{sf}} = 0.7$ kOe. Two types of experiments with different micro-strips arrangement were performed. The schematic arrangement of micro-strips, their EA and the annealing field (H_{ann}) at TMT in two type of experiments are shown in insets in figures 4 and 5. In all the cases, the annealing field was directed along the bisector of this angle between micro-strips.

For micro-strips with various width (from 20 to 80 μm) we obtain the same tendency. The magnetoresistive plateau on field dependences was observed in the positive or negative field region depending on the EA small angle deviation to the left or to the right from H_{sf} (figures 4 and 5). Since the magnitude of the magnetoresistance of a nanostructure depends on the angle between the magnetizations of the free and reference layers, and \mathbf{M}_p and \mathbf{M}_r are exchange-coupled, it can be concluded that PD in two micro-strips after TMT are oppositely directed. We reveal that created PDs depend on the deviation of EA in micro-stripe from H_{sf} . Shape anisotropy did not affect the deviation even for micro-strips with width 20 μm .

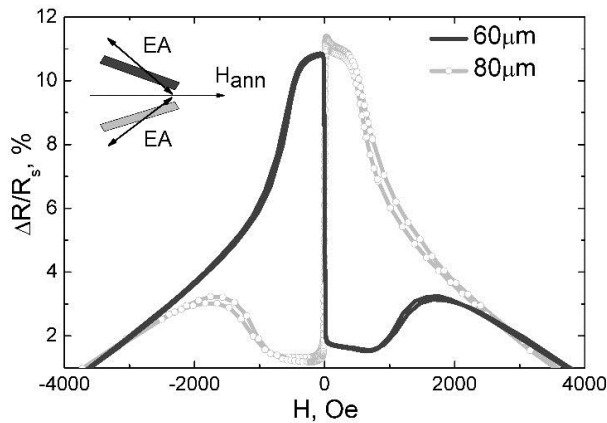


Figure 5. Field dependences measured for micro-strips with width 60 and 80 μm after TMT. Inset shows schematic arrangement of micro-strips, EA and the annealing field (H_{ann}) at TMT.

Apparently, EA is the factor affecting the direction of rotation of a pair of reference and pinned layers during a spin flop transition.

3.3. Full Wheatstone bridge configuration

As it was reported in [7] characteristic field of shape anisotropy for micro-strips with width from 20 to 100 μm varies from 4.1 to 0.8 Oe. On the other hand the characteristic field of uniaxial anisotropy in spin valve is close to 10-15 Oe [8]. To observe the affect of shape anisotropy we choose the micro-strips of 2 and 4 μm width.

Wheatstone bridge configurations were formed with micro-strips 2 μm and 4 μm width (figure 6). The working length of the strips was 300 μm . EA was directed along the long diagonal of the bridge circuit. Sensor elements R1, R2 and L1, L2 deviated from EA by 15° to the right and left, respectively. TMT of the Wheatstone bridge was carried out in two stages. The first stage included annealing in a field of -9 kOe, directed along the EA, during 10 minutes at a temperature of 180°C . This procedure was aimed to form $\text{PD} \parallel \text{EA}$ mutual orientation. The second stage was a similar annealing with subsequent cooling in a magnetic field $H_{\text{sf}} = 0.9\text{kOe}$. It is important to direct H_{sf} as close as possible to EA. We need to avoid forming of new pinning directions caused by deviation of H_{sf} from EA.

A new $\text{PD} \perp \text{EA}$ was obtained as a result of TMT in each micro-strip. This is confirmed by the magnetoresistance curves measured in the field $H \perp \text{EA}$ shown in figure 7. The PDs of L elements is opposite to PDs of R elements of the bridge. Shape anisotropy of micro-strips is a factor provoking the rotation of PDs in opposite directions.

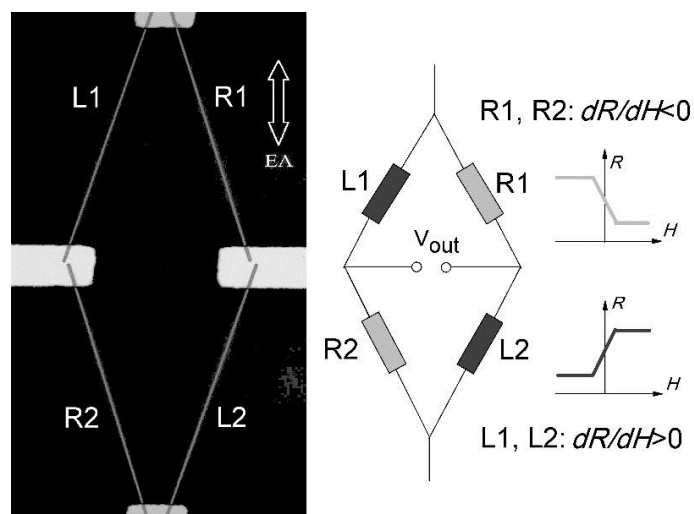


Figure 6. Micrograph and electrical circuit of a full Wheatstone bridge.

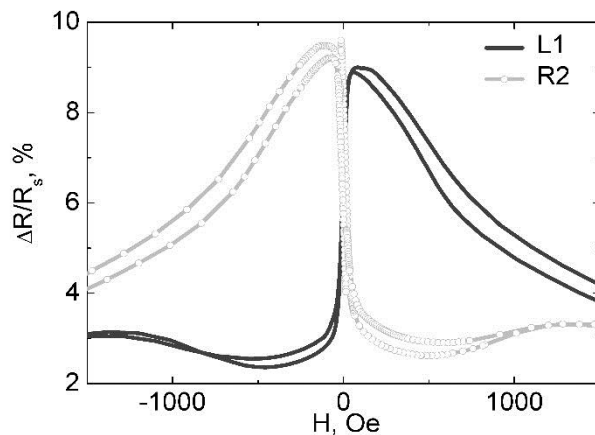


Figure 7. Field dependences of magnetoresistance of Wheatstone bridge the elements R2 and L1 with strip width 4 μm .

Thus, using a single TMT the sensor elements with $dR/dH > 0$ and $dR/dH < 0$ (positive and negative differential response) were fabricated in full Wheatstone bridge.

We must note some decrease of magnetoresistance and change of the shape magnetoresistive curve which happens after TMT. We suppose that choosing parameters of second TMT can improve the result.

4. Conclusion

It has been established that thermomagnetic treatment in the field corresponding to the spin-flop state of the SAF allows to obtain almost anti-parallel PDs in different sensor elements of the bridge circuit. The factor determining PD in a separate sensor element during thermomagnetic treatment can be both the direction of EA and the anisotropy of the shape of the micro-object. Direction of the uniaxial anisotropy has a greater influence on the formation of PD then shape anisotropy.

Using a single thermomagnetic treatment, the positive characteristic (dR/dH) was obtained in the two sensor elements of the full Wheatstone bridge, and the negative characteristic (dR/dH) in the other two elements.

Acknowledgments

The research was carried out within the state assignment of Minobrnauki of Russia (theme “Alloys” AAAA-A19-119070890020-3 and “Magnet” AAAA-A18-118020290129-5), supported in part by RFBR (project No. 19-02-00057) and UD RAS (No. 18-10-2-37).

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